Biobased Industry Opportunity Scan
Task I –Draft Report
August 8, 2005

This draft report constitutes the first deliverable in the Biobased Industry opportunity scan. The report was developed under the direction of the Wisconsin Department of Agriculture, Trade and Consumer Protection by the Energy Center of Wisconsin, the Center for Technology Transfer, GDS Associates, Resource Strategies Inc. and the University of Wisconsin Center on Wisconsin Strategy, and is presented to the Governor's Biorefining Consortium in order to provide a broad, first-cut overview of how Wisconsin might increase the value it derives from its biomass resource.

Our objective in this first task was to narrow the field of biobased technology options to be considered in the next phase. To do so, we defined the *resource-product chain* (RPC) as the basic unit of our research. An RPC links one biobased feedstock to one refining process and one final product. Below, we describe the process used to arrive at the proposed field of RPCs. Following the description of our ranking process is a series of process descriptions and eight graphically presented *process suites*, which show all the feedstocks that can be used for a given process and all the products that can result.

We recommend eight process suites for further consideration in Phase Two of this project. In Phase Two, we will analyze these opportunities in detail, determining which suite or suites are most promising for different regions in Wisconsin based on geographic information such as feedstock concentrations, existing capacity and feedstock transportation costs. With regard to biorefining, Wisconsin's potential sustainable advantage can only be defined geographically—biorefining is about finding the best use of organic and naturally occurring resources, and the economics typically do not allow these resources to be transported very far. Only by assessing where the resources currently exist—and, more importantly, where multiple resources that can be co-processed exist adjacently—can we determine which technologies will deliver the highest additional value from an area's resources while minimizing feedstock transportation costs. Moreover, biorefining is such a young field that there are very few data points we can clearly identify other than the geographic location and concentration of existing feedstocks and the transportation costs for those feedstocks. Production functions of the sort normally analyzed in an economic development plan are, for many emerging bioenergy and bioproducts markets, purely speculative.

Once we have mapped our process suites to specific locations in the state, we will consider the potential products resulting from these processes as the final element of the cluster. We will then perform a detailed assessment of a limited number of these clusters, including technology cost, product cost, market potential, expected environmental impacts, permitting requirements, labor force requirements, job creation potential and related factors. The Phase One analysis contains a cursory look at many of these issues, but they will be considered in depth in Phase Two.

To create the RPCs to be considered, we connected the feedstocks, processes and products catalogued by the Wisconsin Biorefining Development Initiative in 2004. This outlined the vast majority of possible RPCs for Wisconsin, and we added and modified individual elements as necessary.

Our next step was to determine which of the more than 650 possible RPCs had the greatest actual market potential for Wisconsin. Based on the team's experience evaluating and demonstrating biorefining processes and other new technologies, we developed a series of screening questions for each RPC. These questions capture the issues we determined to be most critical to the successful implementation of a biobased technology, with a special emphasis toward the unconventional aspects of this technology adoption (e.g. it will typically not be a matter of simply getting an existing factory to purchase a new piece of equipment). Our screening questions were as follows:

1. Is the feedstock currently found in large quantity in Wisconsin?
2. Is the feedstock available in greater quantities in Wisconsin than in neighboring regions?
3. Would the available quantity of the feedstock change if this RPC had a positive net present value?
4. If currently available, is the feedstock geographically concentrated for other purposes?
5. Are current quantities or concentrations sufficient to achieve economies of scale?
6. When considering primary crops, are there agricultural benefits associated with this crop compared to other crops? (e.g. improved soil quality, improved productivity, reduced cost of planting/harvest)
7. When considering primary crops, what is the expected yield per acre of refinable biomass from this crop?
8. When considering primary crops, what is the expected cost per acre of generating refinable quantities of this crop?
9. When considering primary crops, are there other markets for this crop besides refining? (i.e. What else can you do with corn or switchgrass?)
10. When considering secondary feedstocks, what is the relative cost per ton of refinable biomass?
11. Is there at least one commercial scale example of this process currently in existence?
12. Relative to other biorefining processes, what is the potential for a positive return on investment using this processing technique?
13. How much value is added in going from feedstock to product by using this process?
14. How accessible is this technology? (i.e. How easy will it be to acquire the technical expertise necessary for this process?)
15. How would this process interact with existing industry product streams?
16. When considering secondary feedstocks, would this RPC impact wastestream management?
17. Would this RPC result in a saleable product (as opposed to being consumed on site)?

18. Does a market currently exist for this saleable product?
19. Is the product produced for sale as a final product or will it require further processing?
20. Would this RPC have a positive net energy output?
21. Would this RPC solve other process chain issues not covered by the preceding questions?
22. What would be the expected impact of an incremental increase in regulatory or financial incentives for this RPC?

In our first-cut Phase One technology screen, we scored each RPC on a three-point scale (-1, 0, 1), with a fourth response (X) used when a question revealed the fatal flaw of an RPC. For instance, while it is technically feasible to use alfalfa for pyrolysis to make bio-oil and char, alfalfa is already used in far more valuable processes. Thus "alfalfa pyrolysis" warranted an X in the value-added question.

These scores were summed to provide a total score for each RPC.[1] This approach will allow DATCP to revise these scores in the future, as technological maturity, feedstock availability, product markets and other variables alter the potential value of these chains. It will also allow comparison between existing RPCs and as-yet-unidentified RPCs; while the scoring is not strictly objective in that two people with similar knowledge could score an RPC differently, the existing scores will, if considered, allow a third party to score the new RPC with sufficient context to make comparisons. Such a comparison would not provide a fine level of evaluative detail, but would successfully characterize how a new RPC's potential relates to those of RPCs that have already been explored.

The RPCs were then aggregated by their associated biorefining process into process suites. In almost all cases, most of the relevant technologies can simultaneously process multiple feedstock inputs and create multiple final products. The suites therefore allow us to look at the process as a whole and analyze the specific technical or policy challenges facing it, from barriers growing the feedstock to barriers bringing a particular product to market. Rather than singling out a particularly abundant feedstock and wondering what can be done with it, process suites allow us to organize feedstock supplies by geographic regions as described above.

For each process suite, the feedstocks are divided into three categories:

- *Anchors,* which in and of themselves could justify a facility utilizing the featured biorefining process
- *Supplements,* which could profitably be combined with other feedstocks at such a facility
- *Marginal* feedstocks, which could be added to the process if they are readily available but either already have a high-value use or are not worth collecting (in

[1] It would have been appropriate to use an algorithm that gave a greater weighting to certain questions in the total score, since some questions are clearly more critical than others. For a first-cut evaluation whose purpose was to compare RPCs, however, the unweighted sum was deemed sufficient.

most cases, these are the feedstocks whose RPC for this process included a score of X)

We made a distinction between anchor, supplemental and marginal feedstocks by considering individual questions within the evaluation matrix, such as, "Is the feedstock currently found in large quantity in Wisconsin?" "Is there at least one commercial scale example of this process currently in existence?" and "How much value is added in going from feedstock to product by using this process?"

On the process suite diagrams, feedstocks separated by a dotted line are likely to be found in proximity to one another and are expected to combine in sufficient quantities to be considered an anchor (e.g., pomace combined with fruit and vegetable processing wastewater could be sufficient to anchor an anaerobic digester near a food processing facility). Colored flags to the right of some feedstocks and to the left of some products indicate cases in which certain products only result from the processing of certain feedstocks—for instance, pyrolysis char can be used to make charcoal briquettes, but there is only a market for briquettes made from woody feedstocks.

While performing this analysis, it became clear to our team that there are also anchor *processes*—that is, technologies with the potential to add sufficient value to regional resources such that they could warrant their own processing facility in Wisconsin. In the end, we only presented those process suites that we identified as anchor processes in Wisconsin. The other processes—aerobic digestion and composting, catalytic conversion to hydrogen and hydrocarbon fuels, thermochemical liquefaction and vitrification—all provide significant benefits when implemented but were not deemed to be appropriate anchors given Wisconsin's near-term resources and markets. Greater detail on each process (and, if applicable, the decision not to classify it as an anchor) is given in the following section.

One shortcoming of the Wisconsin Biorefining Development Initiative relative to this effort is that the WBDI focused on remediation of existing abundant biological resources, principally waste streams. A complete picture of biobased industry in Wisconsin needs to also consider those processes that bring new value to primary feedstocks (e.g. crops). One such process is extraction, which has many varieties—for instance, the anchor process of esterification/transesterification will often require lipid extraction to extract the esterifiable lipids from a feedstock. Sometimes, however, extraction can directly produce high-value materials from feedstocks, and effort will be spent in Phase Two to determine which feedstocks have high-value products that can be extracted.

Other important processes that are particularly pertinent when considering primary feedstocks are bioreactors and biosynthesis. A bioreactor uses organisms for biochemical reactions, a definition that applies to anchor processes such as anaerobic digestion and fermentation but also includes metabolic pathway engineering and genetically engineered plants, animals and microorganisms. If a plant is genetically modified to produce a specific chemical that can later be extracted, for instance, that plant would be a bioreactor, as would a fuel cell that uses microbial digestion to produce its hydrogen ions and electrons. Similarly, biosynthesis refers to the production of complex compounds from biobased catalysts (as opposed to organisms). These technologies were not included in any RPCs or subjected to suite-level analysis because of their significant near-term barriers and because the potential feedstock and product pairings are innumerable, but like other nascent processes—including many that may be unknown at this time—they are extremely promising and their potential to transform our economy is significant.

The process suites that follow present numerous pathways for refining Wisconsin's biomass resources, with products ranging from liquid fuel to specialty chemicals. Each pathway has its barriers and none alone is a "silver bullet" technology that will make Wisconsin a prominent player in the bioeconomy. Coupling this information with further technical expertise, extensive discussions with players at every level of the industry (or potential industry), and careful geographical analysis in Phase Two will produce schematics for potential Wisconsin biorefineries, which we can combine with the economic analysis portion of this project to indicate how the state can best direct its efforts to develop Wisconsin's bioindustry.

Process Descriptions

Aerobic Digestion/Composting

- Aerobic digestion and composting use oxygen-dependent bacteria to decompose organic material. The process requires extensive air flow.
- Aerobic digestion is used for wastewater treatment; composting is used for high-solid-content feedstocks. Both wet and dry feedstocks require oxygen, which can be provided by simple mechanical turning for composting, but wet feedstocks may require more expensive aeration.
- Aerobic digestion and composting convert organic materials into carbon dioxide, water and solids. The solids are typically low value but nutrient-rich. The solids can be used as soil amendment but may require further processing.
- Aerobic digestion and composting are widely used. However, since these processes do not create products of significant additional value, they are insufficient to act as the foundation of a biobased industry.

Anaerobic Digestion

- Anaerobic digestion consists of bacterial decomposition of organics in an oxygen-free and temperature-controlled environment. Numerous commercial operations currently exist.
- The process can use a wide range of feedstocks but bacterial colonies are intolerant of large variations in feedstock qualities (e.g., temperature, moisture content, acidity). Anaerobic digestion is generally used for relatively high moisture feedstocks (i.e., 13-0.5% solids).
- Anaerobic digestion directly produces valuable products including methane, animal bedding, and soil amendments, and provides multiple on- and off-farm benefits outside traditional markets, such as odor control.
- The technology is well-established, but barriers limiting widespread adoption remain.

Biomass Gasification

- Biomass gasification refers to a class of low-oxygen, high-temperature (600º to 1000ºC) processes which decompose complex biomass structures into simpler gas molecules. There are a number of patented processes which generally require large volumes and therefore large capital outlay.
- Biomass gasification can be used to process a wide variety of feedstocks so long as the moisture content is below 50%. A consistent feedstock stream is desirable since changes in feedstock will require process adjustments and changes in product quality.
- Biomass gasification produces combustible gases which can be used as a natural gas replacement fuel. Depending on the feedstock and the gas quality requirements, specialized gas-cleaning processes may be needed to produce a final product.
- While well commercialized, the process' economics and needs for large scale presently make this a niche process. Vendors are beginning to offer build, own, operate business models, which may offer a viable alternative to large natural gas users with large amounts of low-cost biomass available nearby. Gasification of pulp mill black liquor is viewed favorably by Wisconsin paper companies. Future improvements in the catalytic conversion of the product gas to transportation fuels will improve economics.

Catalytic Conversion

- In this context catalytic conversion refers to a class of process techniques including (but not limited to) aqueous-phase reforming and Fischer-Tropsch fuel production. (Esterification/transesterification is considered separately.)
- Catalytic conversion can start from a wide variety of potential feedstocks. The most important feedstocks for consideration will most likely be byproducts of other biorefining processes (e.g., glycerin from biodiesel production or pyrolysis oil).
- Catalytic conversion products will include a mixture of fuel-grade compounds (including hydrogen) which could be processed for sale or burned for thermal energy.
- In the Phase One analysis, catalytic conversion was identified as a supplementary process. As such it is not expected to be the basis or foundation around which any bioindustry is built. However, catalytic conversion offers an important link in several potential value chains (for example, glycerol to hydrogen) and may therefore become indispensable to Wisconsin's bioindustry when coupled with other processes.

Combustion

- Combustion is the simplest form of bio-refining; however, there are varying degrees of sophistication in combustion systems. Using biomass to co-fire a coal boiler or power plant can be done with a small loss in efficiency but also a reduction in emissions. Other, more advanced combustion techniques (such as fluidized bed combustors and pelletized biomass fuel) are in various stages of commercialization.
- Almost anything organic will burn, but low-moisture biomass is preferred for combustion, as opposed to high moisture biomass like manures, fats, grease or offal.
- The most useful product of combustion is thermal energy which can be used in boilers, as process heat or to drive a steam turbine to produce electricity. Combustion also produces volatile gases (mostly carbon dioxide) and ash. In given situations, the ash may represent a disposal challenge; in other situations it may have minimal value as inert fill.
- Under the same criteria that excluded other processes, combustion was nearly not included as an anchor process around which a biobased industry is likely to form. This is due largely to the fact that combustion eliminates rather than builds the potential value of the feedstock and represents the end of the value chain. Having said that, it has been argued that combustion represents the simplest technology and therefore could potentially act as a stepping stone to other more sophisticated refining technologies as handling and logistical challenges are addressed.

Fermentation of 6-carbon sugars

- Fermentation of 6-carbon sugars is a biological process in which enzymes produced by microorganisms catalyze chemical reactions that break simple sugars into lower molecular weight materials.
- 6-carbon sugars are found in sugar crops (such as sugar beets and fruit), waste beer and milk and are easily derived from the starches found in the fruits, seeds or tubers of many plants (including field corn, sweet corn, potatoes, oats, winter wheat and barley). The microorganisms needed to ferment these sugars are widely occurring in the plant and animal world. Extraction of sugars from lignocellulosic material is more difficult and is dealt with separately.

- The most common product of fermentation is ethanol, at 50,000 tons per year worldwide. Other products include other alcohols, antibiotics, enzymes, monosodium glutamate, citric acid and other organic acids which are important as building block materials to potentially compete with petrochemical-based refineries.
- Sugar fermentation offers a platform for a high-value-added industry providing a broad base of products. Development work in this area is intense and ongoing. Current corn-based production facilities are expected to face strong competition from lignocellulosic fermentation refineries in the future but it is unclear when that competition will mature.

Fiber Composites Manufacturing

- Fiber composites manufacturing is the process of converting biomass into a usable physical or mechanical form. Fiber composites manufacturing can be split into three major categories: traditional panel products (TPP), thermoplastic composites (TC) and fiber-cement composites.
- Feedstock requirements depend on the process and product. Fiberboard can be made from a wide variety of feedstocks but works best with high volumes, moderate moisture content (15-20%) and steady supply. Thermoplastic composites require a dry and very consistent feedstock such as wood flour. Paper mill sludge is a candidate for fiber-cement composites which are generally more tolerant of feedstock variability.
- Fiber composite manufacturing covers a broad and growing range of products including organic, plastic and cement composites.
- Fiber composite manufacturing offers significant growth opportunities in several areas as market acceptance increases and additional opportunities are identified. Fiber composites manufacturing offers an opportunity for bio-based products to reach new, less traditional industries and applications.

Hydrolysis and Fermentation of Lignocellulosic Biomass

- Cellulose, hemicellulose and lignin are the three main constituents that give plants rigidity. This process uses two steps to capture fermentable sugars from one or both of the first two components listed. First, hydrolysis uses one or a combination of acids, steam or very specific enzymes to break the chemical bonds in which the sugars are trapped in the cellulose or hemicellulose. Once freed into distinct sugar molecules, a tailored fermentation process is used to convert these sugars into useable products.
- Lignocellulosic biomass is readily available and currently underutilized. Examples of potential feedstocks include corn stover, forest residues and grasses. Paper companies are also researching techniques for extracting hemicellulose prior to pulping. This hemicellulose would otherwise be a waste stream later on. Hydrolysis and fermentation processes must be specifically designed for a specific feedstock.
- The products of lignocellulosic fermentation include ethanol and building blocks for specialty chemicals. In addition, unfermentable byproducts, such as lignin, can be dried and combusted for heat and power for the process. The type and quantity of products will depend on the feedstock.
- This process is viewed as the future for ethanol and high-value chemical products from low-value biomass. Large amounts of research and development are being funded throughout the world. Biorefineries using this process will be extremely large and capital

intensive. It remains to be seen which (if any) Wisconsin feedstocks would prove sufficient in abundance and/or concentration for this type of large-scale refinery.

Pyrolysis

- Pyrolysis is the thermal decomposition of feedstocks at high temperatures without oxygen. There are currently commercial operations in Wisconsin.
- Pyrolysis can use nearly any biomass material. Fast pyrolysis requires low moisture content (<10%) and small particle size (1-2mm is desirable).
- Pyrolysis results in varying proportions of combustible gas, liquid products and char depending on the feedstock and process tuning. Few established markets for immediate products currently exist, but the process has potential to produce a wide range of value-added products and compounds.
- EU organizations have high hopes for production of liquid fuels from biomass using (mostly fast) pyrolysis, but further development of refining/extraction techniques and markets for pyrolysis product derivatives will likely be needed to make the process profitable.

Thermochemical Liquefaction

- Thermochemical liquefaction converts a liquid slurry of biomass and organic matter to oxygenated hydrocarbon oils, char and gases through a wide variety of patented high-temperature, high-pressure processes. This process is intended to mimic nature's process of converting organic matter to hydrocarbons and generally requires a large capital outlay.
- A wide variety of feedstocks can be processed by thermochemical liquefaction; however, for optimal performance a single feedstock stream is preferred.
- Thermochemical liquefaction results in a combination of combustible gases and hydrocarbon oils. Biomass feedstocks produce a larger portion of combustible gases while offal or other organics produce larger amounts of hydrocarbon oils.
- Thermochemical liquefaction is still an emerging technology for specialized applications and was therefore not considered to be an anchor process for this study. Wisconsin's main interest in this process may be its ability to gasify high-moisture biomass waste streams and to potentially destroy prions in livestock infected with BSE.

Tranesterification/Esterfication

- The process of esterification/transesterification is used to convert fatty acids (vegetable oils, animal fats, etc.) into usable chemicals. This can include synthetic fibers, such as polyester, or fuels such as biodiesel. The process requires the presence of an alcohol and a catalyst (such as lye). It is a well understood chemical process and is commercially available.
- The sources for fatty acids are many and widespread. Logical concentration points are waste cooking oil, animal rendering byproducts and plant oils.
- The raw fatty acids determine, in part, the final product. However, further processing can allow for more flexible supply options. Additionally, when used as biodiesel, the final product can be a mix of hydrocarbon chains. Biodiesel is a growing market. Primarily biodiesel is used as an additive to petroleum-based diesel fuel. The markets for synthetic products are limited, though offer long-term future potential.

- A major product from the transesterification process is glycol. The increased production of biodiesel will quickly reach the point of supplying the world’s current demand for glycol and help drive glycol prices down. A large worldwide surplus of low-priced glycol may open up new opportunities for glycol-based products and innovation, adding further value to the transesterification process.

Vitrification

- Vitrification is an exothermic process in which dried waste streams are heated to very high temperatures in oxygen-rich furnaces. Organic materials and minerals turn to ash and then a molten glass. The molten glass is removed from the furnace and water-quenched to produce inert glass aggregates.
- Vitrification could be applied to any sludge-like process effluent which is rich in both organics and minerals. Paper mill residues, municipal wastewater and manures are possible feedstocks. Vitrification can be used to capture and stabilize hazardous waste and heavy metals.
- Vitrification results in a low-value glass aggregate that can be used as inert fill for concrete and asphalt or as an abrasive on flooring and shingles.
- Vitrification is not believed to add sufficient value to act as a bio-industry anchor.

Anaerobic Digestion

Feedstock

Anchors

- Manure (dairy)
- Manure (poultry)
- Manure (swine)
- Municipal biosolids
- Pomace, scraps & spoilage
- Wastewater (fruit & vegetable processing)
- Scrap/ spoilage (meat packing)
- Inedible offal
- Wastewater (pulp & papermaking)
- Whey

Supplements

- Municipal woody waste
- Source-separated solids
- Spent (brewers) yeast
- Spent hops (trub)
- Waste beer
- Waste cooking oil
- Wastewater (meat packing)

Low value

- Alfalfa
- Beef tallow
- Corn stover
- Crop field residues
- Crop processing residues
- Edible offal
- Forage grasses
- Municipal solid waste
- Paper mill residue
- Spent grains
- Switchgrass

Process

- Anaerobic digestion
- Two-stage digestion
- Batch processing

Product

- Biogas
- Effluent solids
- Liquid effluent
- Specialty acids
- Class A biosolids

Additional Process

- Combust
- Scrub/ upgrade

Sub-Products

- Heat
- Heat and electricity
- Pipeline/ sales
- Soil amendment
- Bedding
- Other products
- Soil amendment
- Disposal

Further Processing

- Aerobic digestion / composting
- Biomass gasification
- Pyrolysis

Biomass Gasification

	Feedstock	Process	Product	Additional Process	Sub-Products
Anchors	Pulp mill black liquor	Biomass gasification	Biobased fuel gas and syngas		Low-energy fuel gas
	Municipal solid waste			Scrubbing	Medium-energy syngas for boilers
	Debarking waste			Steam reformation	Syngas for turbines, fuel cells, etc.
	Forest residues			Fermentation	Ethanol
	Sawdust				Specialty chemicals (acetic acid, PHA, etc.)
	Waste wood chips			Catalytic conversion	Renewable Fischer-Tropsch hydrocarbon fuels (methanol, etc.)
	Wood chips		Ash		Soil amendment
Supplements	Corn stover				Inert fill
	Crop field residues				
	Crop process residues				
	Forage grasses				
	Manure (dairy)				
	Manure (poultry)				
	Manure (swine)				
	Spent (brewers) yeast				
	Spent grains				
	Spent hops (trub)				
	Switchgrass				
Low value	Alfalfa				
	Paper mill residue				

Combustion

	Feedstock	Process	Product	Additional Process	Sub-Products
Anchors	Municipal solid waste	Combustion	Thermal energy		Heat
	Waste wood chips			Steam turbine	Heat and electricity
	Wood chips		Ash		Soil amendment
Supplements	Corn stover				Inert fill
	Crop field residues				
	Crop processing residues				
	Debarking waste				
	Forest residues				
	Manure (dairy)				
	Manure (poultry)				
	Sawdust				
	Spent hops (trub)				
	Switchgrass				
Low value	Alfalfa				
	Forage grasses				
	Manure (swine)				
	Spent grains				

Esterification/Transesterification

	Feedstock	Process	Product	Additional Process	Sub-Products
Anchors	Inedible offal	Lipid extraction and/or esterification/ transesterification	Biodiesel		
Anchors	Rapeseed (canola)		Full-fat flour		
Anchors	Scrap/spoilage (meat packing)		Glycerin	Catalytic conversion	Hydrogen
Anchors	Soybeans		Crop fibers		Corn fiber oil (pharmaceutical)
Supplements	Waste cooking oil				Corn fiber gum
Supplements	Beef tallow				Bulking agents
Supplements	Edible pffal				Glucose
					Pesticides
					L-arabinose (sugar)
			Meal		Foodstuffs
					Feed

Pyrolysis

	Feedstock	Process	Product	Additional Process	Subproduct	Further Processing
Anchors	Forest residues	Pyrolysis	Char		Boiler fuel	
	Manure (dairy)				Charcoal for briquettes	
	Municipal solid waste				Soil amendment	Conversion to fertilizer
	Sawdust			Activation	Carbon for filtration	
	Waste wood chips			Combustion	Thermal energy	
Supplements	Corn stover		Pyrolytic bio-oil	Extraction processes	Resins	
	Crop field residues				Food additives	
	Debarking waste				Other compounds	Catalytic conversion
	Forage grasses					Fermentation
	Manure (poultry)				Levoglucosan	Fermentation to specialty chemicals
	Manure (swine)					
	Municipal woody waste					
	Pomace, scraps and spoilage					
	Spent (brewers) yeast					
	Spent grains					
	Spent hops (trub)					
	Switchgrass					
	Wood chips					
Low value	Alfalfa					

Sugar Fermentation

	Feedstock	Process	Product	Additional Process	Subproducts
Anchors	Field corn grain Sugar crops	Pre-processing and fermentation of 6-carbon sugars and starches	Ethanol Butanol		
Supplements	Waste beer		1,4-diacids (succinic, fumaric, malic) Glutamic acid Itaconic acid Levulinic acid Xylitol/arabinitol 3-hydroxybutyrolactone Acetic (ethanoic) acid Aspartic acid	Multiple processes (often proprietary) and subject of ongoing development	Novel & commodity chemicals, pharmaceuticals
			2,5 furan dioxycarbolic acid 3-Hydroxypropionic acid (3-HP) Glucaric acid Lactic acid Sorbitol 1,3-Propanediol (PDO) PHA (Polyhydroxyalkanoate) polymers		Polymers, plastics, fibers
			Distillers' dried grains with solubles		
Low value	Barley Oats Potatoes Winter wheat				

Ligno Fermentation

	Feedstock	Process	Product	Primary applications
Anchors	Corn stover	Hydrolysis and fermentation of lignocellulosic biomass	Ethanol	
Anchors	Forest residues		Butanol	
Anchors	Wood chips		1,4-diacids (succinic, fumaric, malic)	Novel & commodity chemicals, pharmaceuticals
Anchors	Switchgrass		Glutamic acid	
Supplements	Alfalfa		Itaconic acid	
Supplements	Crop field residues		Levulinic acid	
Supplements	Forage grasses		Xylitol/arabinitol	
Supplements	Municipal solid waste		3-hydroxybutyrolactone	
Supplements	Spent hops (trub)		Acetic (ethanoic) acid	
			Aspartic acid	
			2,5 furan dioxycarbolic acid	Polymers, plastics, fibers
			3-Hydroxypropionic acid (3-HP)	
			Glucaric acid	
			Lactic acid	
			Sorbitol	
			1,3-Propanediol (PDO)	
			PHA (Polyhydroxyalkanoate) polymers	
			Distillers' dried grains with solubles	
Low value	Debarking waste			
Low value	Paper mill residue			
Low value	Sawdust			

Fiber Composites

	Feedstock	Process	Product
Anchors	Corn stover	Fiber composites manufacturing	Durable building materials and finished goods
	Paper mill residue		
	Sawdust		
	Switchgrass		
	Wood chips		
Supplements	Alfalfa		
	Crop field residues		
	Forage grasses		
	Forest residues		
	Waste wood chips		